Atmospheric Calibration for Cassini Radio Science

by
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Abstract

The signals from the Cassini spacecraft that will be used for radio science experiments will be affected by delay fluctuations in the Earth's atmosphere. These fluctuations are dominated by water vapor in the troposphere, and in the case of the Gravitational Wave Experiment (GWE), they are likely to be a limiting error source. A passive remote sensing system, centered around a water vapor radiometer (WVR), has been developed to provide. calibrations of water vapor fluctuations during radio science experiments. During the past two years, most of' the technical challenges involved in the design of this instrument have been overcome and we are ready to begin implementation. We will discuss the performance that has been demonstrated with the current generation of WVR instrumentation and the general design of the package that will be installed at the Goldstone tracking site. In addition, recent results obtained for a comparison of co-located WVRS and Global Positioning System (GPS) receivers will be presented. The possibility of using these results to estimate gradients and/or fluctuations in the dry atmosphere will be discussed.

Introduction

During the long cruise and orbital phases of the Cassini mission, a large number of radio science experiments are possible. One of the most demanding experiments, at least in terms of the support technology required at the ground station, is the Gravitational Wave Experiment (GWE). Figure 1 shows the five major categories of the GWE error budget. *Thermal* is the thermal noise set by the signal-to-noise ratio. *S/C* denotes various sources of error from or on the spacecraft, *Grd Ant* indicates errors due to mechanical or thermal effects on the ground antenna, of which the time dependence is often poorly understood. *Ground* denotes the error contribution by the electronics (including frequency standard) at the ground station, and *Prop* denotes the errors from the propagation medium. We see that the major source of error for time scales longer than approximately 100 sec, will come from fluctuations in the path delay imposed primarily by the Earth's atmosphere along the spacecraft line-of-sight,

The path delay through the atmosphere is composed of two components. The largest, called the dry delay, is due primarily to the well-mixed components of oxygen and nitrogen; it imposes about 2.5 m of extra path delay at the zenith, The second component, termed the wet delay, is due to water vapor which is not well-mixed in the atmosphere. The dry delay changes at the level of a few mm over time scales of many hours or days. The wet delay is typically less than 20 cm at the zenith, but is highly variable over a wide variety of time scales.

Several years ago, our group embarked on an effort to develop a subsystem that would measure water vapor fluctuations along the line-of-sight for the GWE. The requirement is to measure down to elevation angles of 20 deg. and calibrate both uplink and downlink signals to an Allan Standard Deviation of 1.5×10^{-15}. This year, the implementation of this subsystem will begin at our Goldstone tracking station in preparation for the GWE observing sessions that will be held during the spacecraft cruise from Earth to Saturn. This paper presents a brief report on our progress toward achieving the calibration accuracy required by the GWE. The conceptual design of the subsystem and some of the major features is also discussed. Many of these features should be useful in other radio science experiments besides the GWE.

Background

For over 20 years, various groups around the world have experimented with the techniques of passive remote sensing to measure amount of water vapor in the Earth's atmosphere. The conceptual basis is very straightforward and is illustrated in Figure 2. Here, we show the brightness temperature (i.e. the power) as a function of microwave frequency, that would be measured by a power meter (i.e. a radiometer) directed at the zenith, from a sea level observing location, under a standard atmosphere containing 2 g/cm^2 of precipitable water vapor (PWV) that was exponentially distributed.

There are two important features to be noted in Figure 2. First, there is a resonance from the water vapor molecule at a frequency of 22,2 GHz and the strength of this resonance is proportional to the amount of water vapor along the line-of-sight. We use a device called a Water Vapor Radiometer (WVR) to measure the power contained in this spectral line and this device is the heart of our calibration subsystem. The technical challenge is to reliably detect changes in line strength at the level of a few mini Kelvin on time scales up to 10,000 seconds. This implies a radiometer with absolute stability of a few parts in 10^5. In fact, this level of stability has been demonstrated with a laboratory prototype instrument.

The second feature to notice is centered approximately at 60 GHz and represents absorption and emission by a complex of lines from the oxygen molecule. Using radiometer measurements at optimally selected frequencies along the wing of this complex of lines and by tipping the radiometer to various elevation angles, it is possible to estimate the vertical temperature profile of the atmosphere. For this reason, the radiometer is called a Microwave Temperature Profiler (MTP). Estimates of the temperature profile are used to improve the vapor path delay provided by the WVR by roughly a factor of five according to our simulated retrievals. in addition, the. MTP can be fixed at a given elevation and turned slowly in azimuth resulting in an estimate of the horizontal homogeneity of the temperature field around the observing site. This information can be used to estimate horizontal gradients in the dry delay of the atmosphere.

Current Status

When the effort to develop an atmospheric calibration subsystem for Cassini radio science was begun about three years ago, it called for approximate] y an order of magnitude improvement in the then current sensing technology. A careful error analysis of the subsystem was completed and parallel efforts on the major sources of error were begun. Since the subsystem we are building is so much better than anything else in existence, we face the problem of conclusivel y demonstrat ing that we arc indeed achieving the required level of calibration accuracy.

The demonstration problem has been approached by crafting a comparison between W VRs and a highl y precise radio interferometer, i.e. using the techniques of very long baseline interferometry (V] .BI). Figure 3 illustrates the concept of the experiment which has been described in detail by Teitelbaum *et. al.* [1996]. Two large antennas are used to observe a distant radio source but maintain coherence using a common set of oscillator frequencies to heterodyne the received signal, The signal from each antenna is compared to estimate the difference in delay; the geometry and instrumental effects are modeled with high accuracy, and what is left as a residual is dominated by unmodeled atmosphere effects. For these experiments we used two misting WVRs that have been upgraded, placed them near the VI .BI antennas, and observed along the line-of-sight to the radio source as much as possible.

The WVRs each produce a time series of delay estimates which arc then differenced and this di fference is then compared to the delay measured by the radio interferometer as shown in Figure 4. over a roughly 15 hour period, many radio sources were observed with the interferometer at various positions in the sky. Figure 4a shows the residual delay comparison between the interferometer and the WVRS for only those observations for which the WVR could co-point. The VI .BI data shown in Figure 4a shows a residual delay of 44 psec which is reduced by almost a factor of three after calibration with the WVR data. 'l'he remaining residual, of 17 psec, is consistent with current estimates of the noise floor for both the interferometer and WVRs.

Most of the radio sources in this experiment were observed for only three minutes before moving to another source. 1 lowever, three strong sources were each observed continuously for approximately 30 minutes at various periods during the experiment. Figure 4b shows the same comparison between interferometer and W VR as dots Figure 4a but on an expanded t ime scale as wc tracked the source. '1 'his situation approximates the observing strategy that will be used for Cassini radio science experiments and tests our ability to track delay fluctuations. The differences seen in this figure are consistent with the fact that the WVR and interferometer arc sensing slightly different portions of the atmosphere. This is due to the larger beamwidth of the WVR, and its physical offset from the interferometer antenna.

Taken together, the.se two figures give us confidence that it is indeed possible to achieve the nearl y order of magnitude improvement required to cali brate the at mosphere for the G WE. '1 'he top figure indicates that our retrieval algorithms, used to convert the WVR observable to path delay, arc robust over at least a factor of two in atmospheric opacity. This is important because of the need to track the spacecraft from elevation angles of 20 degrees (or lower) to about 55 degrees.

To date, all efforts have concentrated on calibrating wet atmospheric fluctuations. It has not yet been possible to devise a technique to calibrate line-of-sight dry atmospheric fluctuations, which although smaller arc still of interest to the tots] error budget of some radio science experiments. 1 lowever, it may be possible to estimate the magnitude of dry fluctuations even though the line-of-sight can not be calibrated, As evidence of this possibility consider Figure 4. Here, the wet zenith delays estimated from two very independent techniques arc compared. In this experiment which spans 25 days, the wet delay estimated by a WVR is compared with that estimated from a co-located Global Positioning System (GPS) receiver.

The GPS receiver is part of a world-wide network of similar receivers used primarily for geodetic purposes. The data from this network is gathered at JPL and analyzed. One of the estimated parameters is the total zenith atmospheric delay (both dry and wet components) over each receiver. A barometer is used to estimate the total dry delay for the GPS receiver, and subtracted from the GPS estimate of total delay to get the wet delay. 'l'his GPS estimated wet delay, together with simultaneous W VR measured wet delay are shown in Figure 5.

Although close examination of Figure 5 reveals obvious systematic effects, the good agreement over a fairly wide range of wet delay values and the small bias, leads us to be optimistic that there is potential in the GPS data type. During the next year we will investigate whether the difference between the GPS and WV]{ wet delays can really be ascribed to dry delay fluctuations. Also, since the GPS spacecraft cover a wide range of elevation and azimuth around a given receiver, it is possible they can also provide information about horizontal gradients in the dry delay.

Subsystem Design

Figure 6 shows a block diagram of the atmospheric calibration subsystem that we arc now starting to build for Cassini Radio Science. It consists of an Advanced WVR (AWVR), a Microwave Temperature Profiler (MTP), a set of instruments that will measure surface pressure, temperature, relative humidity, wind speed, wind direction, and two cameras, one in the visible and one in the infrared, Depending on the results of the coming years investigations, we may also include a GPS receiver in the subsystem.

'1 'he A WVR will be mounted on a clear aperture antenna having a beamwidth of approximatel y 1 degree, placed near the 34 m antenna that will be used to track Cassini, and commanded to track along the same line-of-sight during radio science experiments. 'l'his new WVR will exceed the stability of existing instruments by almost an order of magnitude more stable than. It will be about a factor of three more sensitive, have a beamwidth approximately 7 times narrower that current WVRS, and be able to track down to elevation angles of20 degrees.

The MTP will also be independently mounted but will not point along the line-of-sight, We have not developed an observing strategy for this instrument yet but most likely it will intersperse tip curves with azimuth scans. The tip curves will be used to estimate vertical temperature profiles which will then be used to refine the retrieval algorithms for the AWVR.

Surface meteorological measure.mmts arc also used to "tweak" the retrieval algorithms for both the A WVR and the MTP. The cameras arc pointed along the boresight of the antenna and provide the experimenter with a picture of sky conditions for both day and night.

The subsystem will provide real-time estimates of line-of-sight path delay, the amount of liquid water (i.e. in clouds), the total zenith delay, surface conditions, and pictures of the sky along the line-of-sight. Everything will be controlled remotely from a radio science workstation located at J]'],. If there is interest by the experimenters and wc can satisfy the DSN security concerns, all of the subsystem output could be put onto the World Wide Web.

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References:

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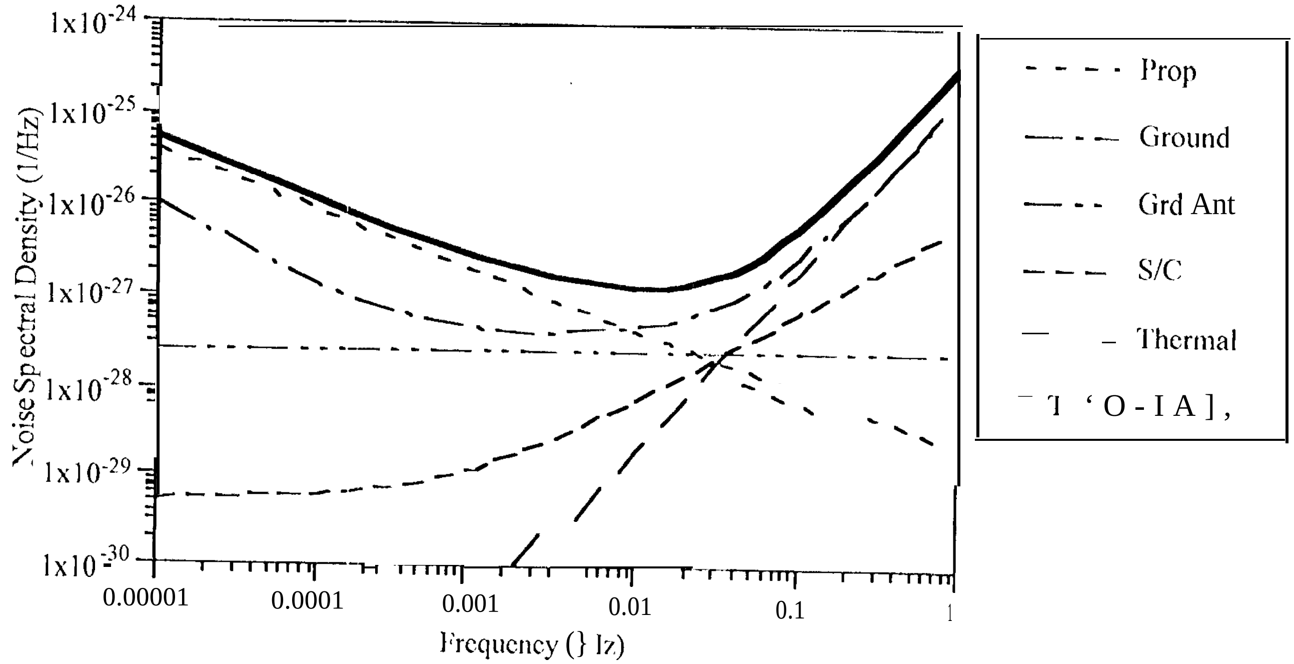

Figure 1 - Doppler error budget for the GWE

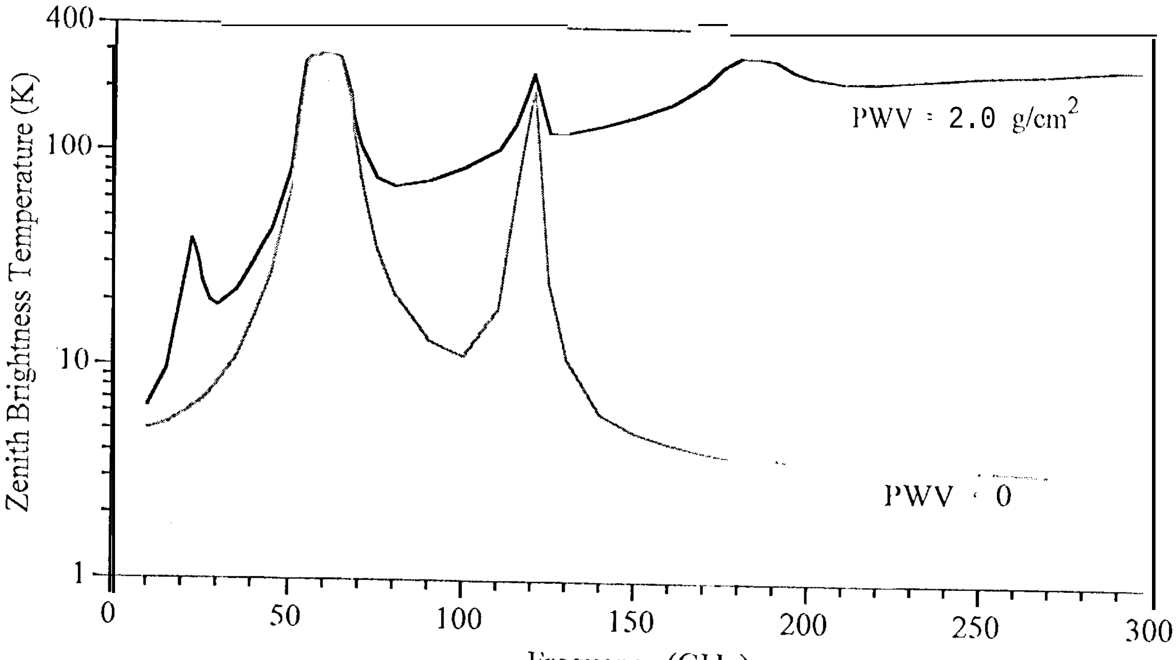

Figure 2- The zenith brightness temperature of the atmosphere between 1 to 300 GHz with and without water vapor.

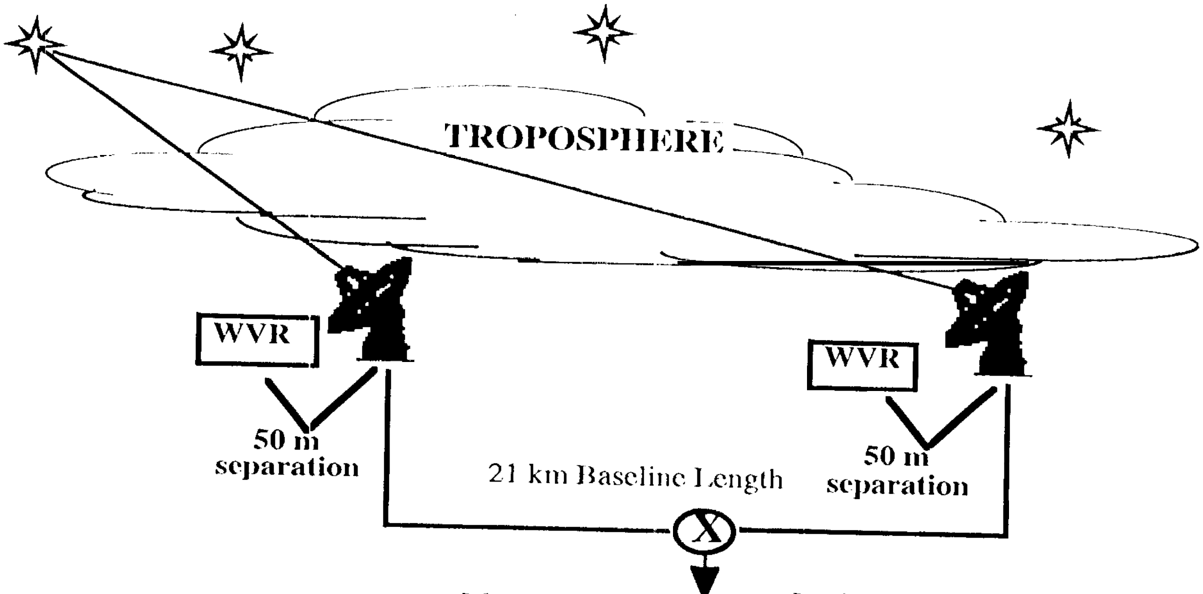

Figure 3 - Comparison of VLBI and WVR delay measurements

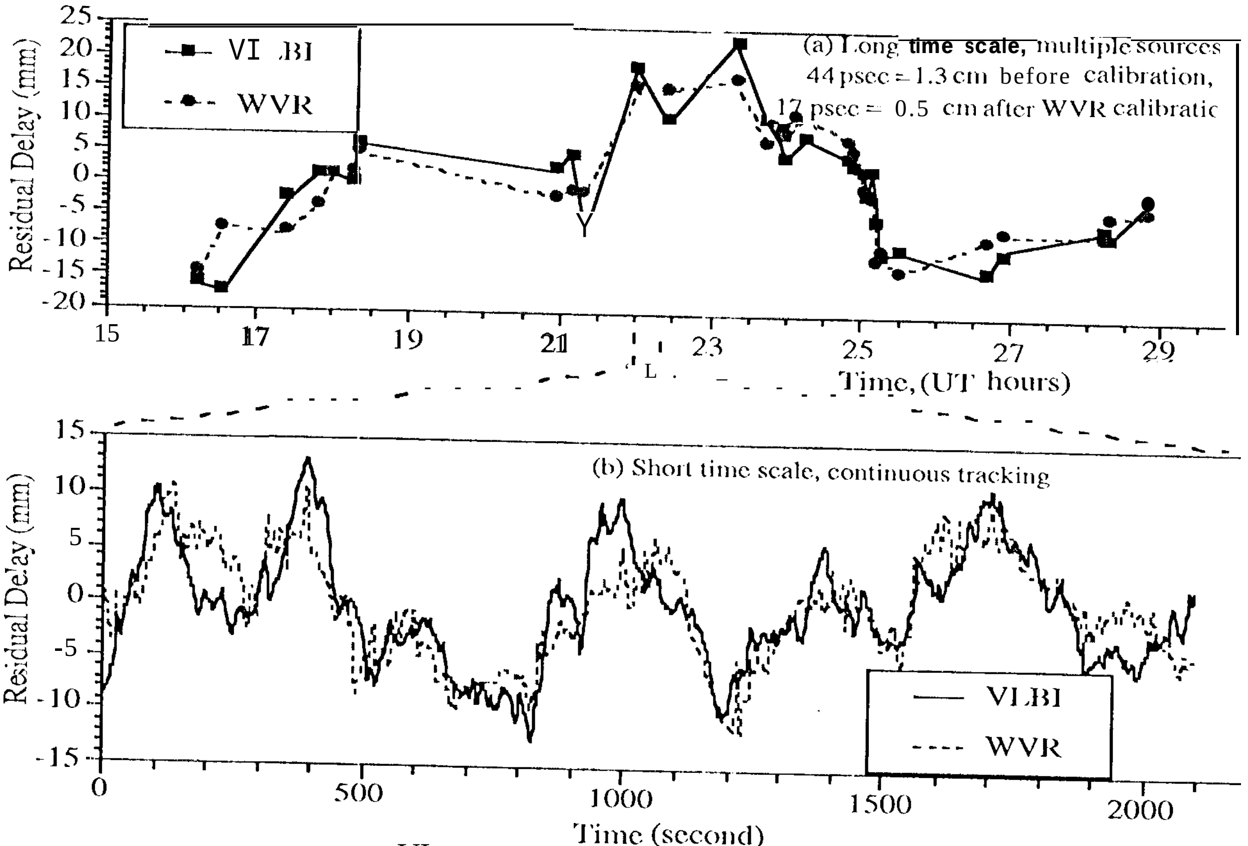

Figure 4 - VLBI/WVR Intercomparison - Goldstone, Sept 1994

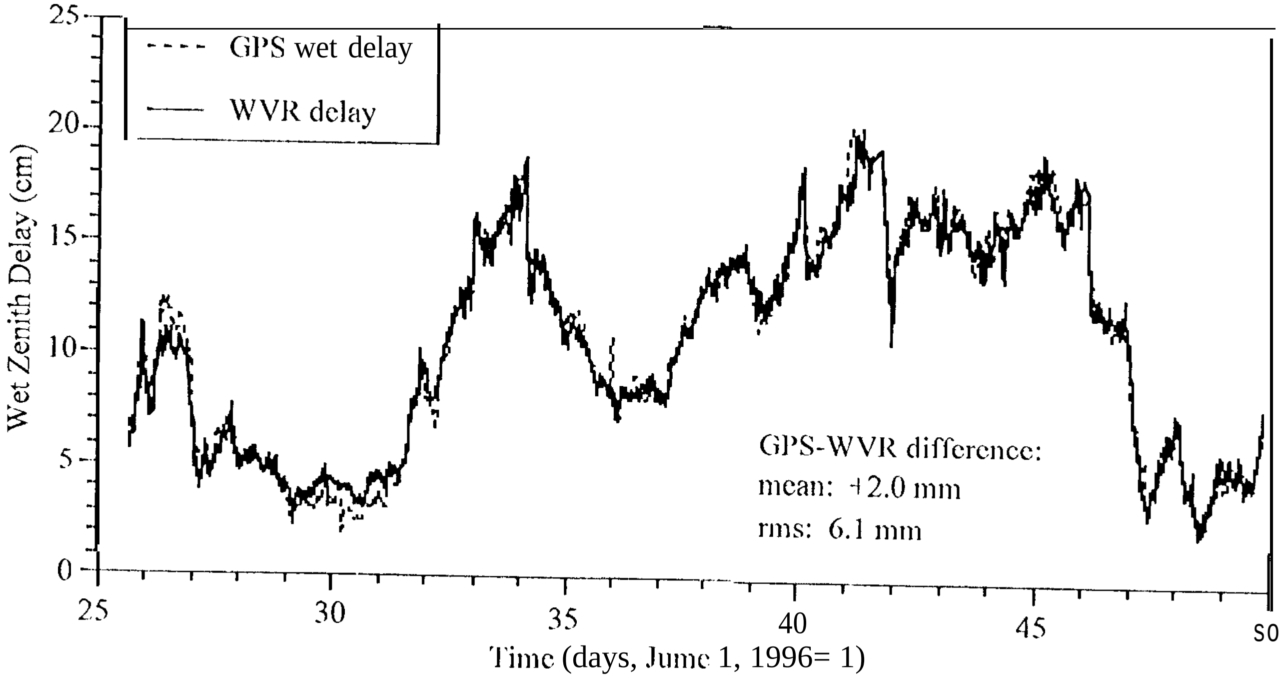

Figure 5- Comparison Of GPS estimates and WVR measurments of the wet zenith delay for a 25 day period in June/July 1996

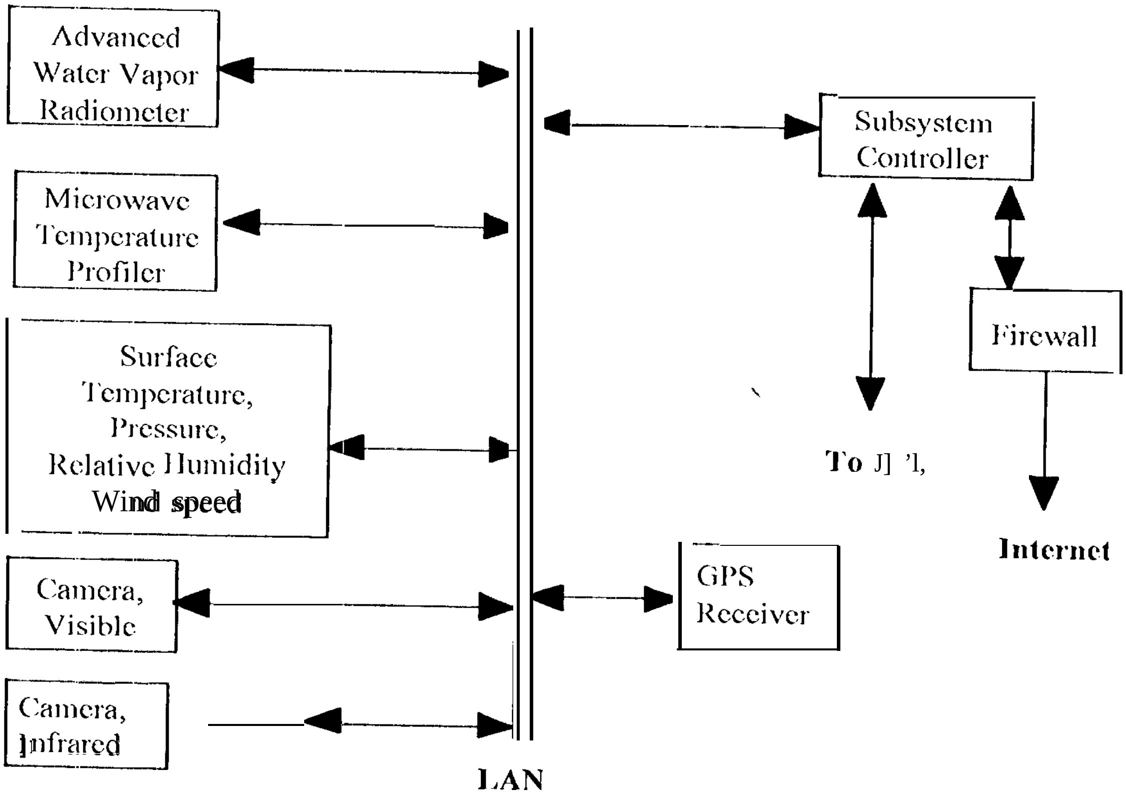

Figure 6- The proposed block diagram of the atmospheric calibration subsystem for Cassini radio science.